Journal of Paleolimnology **30:** 297–306, 2003.

Natural environmental changes and human impact reflected in sediments of a high alpine lake in Switzerland

C. Ohlendorf[1,3,*], M. Sturm[1] and S. Hausmann[2]
[1]*Swiss Federal Institute of Environmental Science and Technology (EAWAG), Überlandstr. 133, CH-8600 Dübendorf, Switzerland*
[2]*Institute of Plant Sciences, University of Bern, Altenbergrain 21, CH-3013 Bern, Switzerland*
[3]*Geomorphology and Polar Research (GEOPOLAR), Institute of Geography, FB 8, University of Bremen, Celsiusstr. FVG-M, D-28359 Bremen, Germany*
**Author for correspondence (E-mail: ohlen@uni-bremen.de)*

Received 24 December 2000; accepted 24 March 2003

Key words: Erosion, Weathering, Sedimentology, Mineralogy, Grain size, Human impact, Climate

Abstract

From the high alpine Sägistalsee (1935 m a.s.l.), 13.50 m of continuously laminated sediments comprising the last 9050 years, were analyzed. Even though Sägistalsee is a high elevation site, human-induced environmental changes start as early as 4300 cal. BP and leave a clearly detectable signal in the mineralogy of the sediments, which is much stronger than the signal from natural environmental changes that occurred before this time. Variations in the physical and mineralogical sediment properties of this clastic sequence reflect erosional changes in the catchment, where almost pure limestone contrasts with carbonaceous, quartz-bearing marl, and shist. The calcite/quartz (Cc/Qz) ratio was found to be most indicative of these changes, which occurred around AD 1850 and at 650, 2000, 3700, and 6400 cal. BP. The first four are interpreted as erosion events, which are related to human-induced changes in the vegetation cover and land use. We associate them to the recent development of tourism and grazing, the medieval intensification of pasturing, Roman forest clearance, and Bronze Age forest clearance, respectively. The Cc/Qz-ratio increases significantly within less than 100 years during these events, reflecting the erosion of unweathered or poorly weathered soils. The time intervals in between are characterized by a gradually decreasing Cc/Qz-ratio and reflect the stabilization or formation of new soils. Only the change at 6400 cal. BP, which represents the initial gradual stabilization of the catchment, is related to the immigration of *Picea abies*.

Introduction

Environmental changes in mountainous regions are mainly the result of climate change and human activity, with the latter often being a response to a change in climate. Mountainous regions are very sensitive to climate changes because the global climate signal is strongly amplified there (Beniston et al., 1997).

Until recently lakes situated in remote areas at high altitudes have been considered to be relatively pristine and therefore record exclusively the effects of climate change rather than human-induced environmental changes. During the past decade it has emerged that mountains (especially the European Alps) have been inhabited by humans as early as 5000 cal. BP (calibrated ^{14}C years before AD 1950). The first significant occupation of high elevation areas in the Alps by humans, which is documented archaeologically, occurred during the Bronze Age, around 4000 cal. BP (Wyss, 1990). During this time clear traces of human impact on vegetation could also be observed in lake sediments near present-day tree-line (e.g., Tinner and Ammann, 1996; Wick and Tinner, 1997; Gobet et al., 2001).

This is the fifth in a series of eight papers published in this special issue dedicated to the palaeolimnology of Sägistalsee. Drs. André F. Lotter and H. John B. Birks were the guest editors of this issue.

Lake sediments form continuous, natural archives provide long environmental records with a potentially high time resolution. But the occurrence of early human impact implies that environmental reconstructions from Holocene lake sediments, even at high elevations, require attempts at disentangling climate-induced changes from anthropogenic environmental effects. The most promising way to handle this is a multi-proxy approach, which we pursued in the framework of the AQUAREAL project (Lotter et al., 1997; Lotter and Birks, 2003).

Another difficulty that is often encountered in sediments from high altitude lakes is the sparcity of organic matter in the sediments, which makes ^{14}C-dating very difficult. The sediments of Sägistalsee are an exception, as sufficient terrestrial macrofossil remains (Wick et al. 2003) have allowed the construction of a robust chronology for the last 9050 cal. BP (Lotter and Birks, 2003).

In high elevation lakes with glaciated catchments, physical, chemical, and mineralogical sediment properties have been used for the reconstruction of past glacier dynamics (Leonard, 1986; Leemann and Niessen, 1994; Ohlendorf et al., 1997; Leonard and Reasoner, 1999). In lakes that are dominated by allochthonous clastic input but without glacial influence, the environmental information that is recorded in the sediments is less clear.

The aim of this study is to investigate the environmental changes that took place during the Holocene in the catchment of Sägistalsee, what consequences these changes had for the limnology of the lake, and how they are reflected in the sedimentary record of the lake. The physical, chemical and mineralogical sediment signatures we determined integrate the effects of both within-lake and catchment processes. In conjunction with other results of this project (Heiri and Lotter, 2003; Hirt et al., 2003; Hofmann, 2003; Koinig et al., 2003; Wick et al., 2003) we attempt to distinguish climate-induced changes from anthropogenic changes in catchment weathering and erosion.

The site

Sägistalsee (46°40′48″N, 7°58′35″E) is situated in the Bernese Alps of Switzerland at an altitude of 1935 m a.s.l. (Fig. 1). The lake has a surface area of 7.25 ha, a maximum depth of 9.7 m and a relatively large catch-

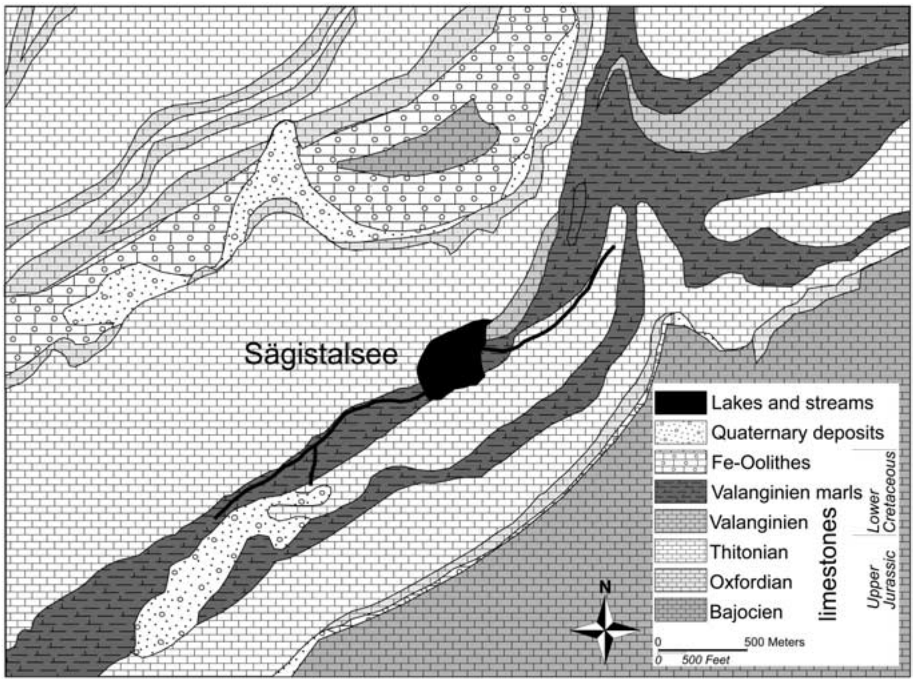

Fig. 1. Simplified geological map of the Sägistalsee catchment (after Günzler-Seiffert and Wyss, 1938; Seeber, 1911). Calcite rich massive black and yellow-brown upper Jurassic limestones occur on the steep northwestern and southeastern slopes. Carbonaceous, clay rich, lower cretaceous schists and marls form the flat northeastern and southwestern basement around the lake.

ment of 362.2 ha (for details cf. Lotter and Birks, 2003). It is situated in a SW–NE oriented depression and receives water through two major inflows from the SW and the NE. Although there is no surface outflow, outseepage occurs along the northern shore (Guthruf et al., 1999). Situated at today's tree-line, 30% of the catchment is presently used as alpine meadows for pasturing.

Geologically, Sägistalsee is located in upper Jurassic and lower Cretaceous carbonaceous rocks of the Wildhorndecke (Fig. 1), a helvetic Alpine nappe (Seeber, 1911; Günzler-Seiffert and Wyss, 1938). The catchment of Sägistalsee is characterized mainly by two differing lithologies. Its smooth north-eastern and south-western slopes are composed of dark marl and carbonaceous schist (lower Cretaceous). They are rich in clay and contain quartz. In contrast, the north-western and south-eastern slopes of the catchment consist of massive black and yellow brown limestone beds (upper Jurassic). Parts of the southern slopes are made of a breccia that sometimes shows siderolithic weathering crusts. Fe-oolithes are present in the northern and north-western part of the catchment (Seeber, 1911). Karst phenomena are frequent, and we interpret the lake as having formed within a doline. Vegetation on the steep slopes of the catchment is sparse.

Methods and measurements

A 13.5 m long sediment core was recovered from Sägistalsee with a Livingstone piston corer operated from the frozen lake-surface in spring 1996 and sampled at 2 cm intervals for analysis of chemical, physical, and mineralogical sediment properties (for details, see Lotter and Birks, 2003).

Freeze dried samples were analysed for inorganic carbon (C_{inorg}) with a coulometer (Coulometric Inc. 5011 CO_2-Coulometer). Total carbon (C_{tot}) was determined with a Carlo Erba CHNS Elemental Analyzer (Model EA 1108), and organic carbon (C_{org}) was calculated from the difference (C_{tot}–C_{inorg}) in 308 samples.

A laser-particle-analyzer (Malvern Mastersizer) was used to determine the grain-size distribution of the sediments < 150 μm in 294 samples. For analysis, 40 mg of the freeze dried sample were suspended in 10 ml of a 15% H_2O_2 solution at 40–45 °C for at least 48 h to remove organic matter and to promote deflocculation. The sediment samples were then rinsed twice with distilled water and centrifuged at 4000 rpm. Prior to measurements the samples were suspended in 3 ml of a 0.01% Calgon solution to prevent coagulation.

The mineral composition of the sediment samples was determined by X-ray diffraction (XRD) of smear slides in 171 samples. For smear-slide preparation approx. 3 mm^3 of sediment were suspended with ethanol in a mortar and ground to < 63 μm. The suspension was then transferred to a glass sample holder and air-dried. Diffraction patterns were recorded with a Scintag XDS 2000 at 45 kV and 40 mA with Cu Kα radiation between 2 and 70°2Θ. In order to have a parameter that is independent of changes in sediment accumulation rates we express changes in the mineralogy as the calcite/quartz (Cc/Qz) ratio. This is the ratio of the calcite 100% peak (peak intensity in cps at 29.406°2Θ, d = 3.035Å) to the quartz 100% peak (peak intensity in cps at 26.665°2Θ, d = 3.343Å).

Following Conley (1988), we used the biogenic silica (BSi) concentrations of the sediments to estimate diatom and chrysophyte palaeo-productivity in the lake. The BSi concentrations were measured by the wet chemical dissolution photometric technique after DeMaster (1981). Because measured concentrations were very small, 95% confidence intervals were determined following Zar (1984).

Bulk dry densities of 20 samples, randomly distributed along the core, were determined using the pycnometer method.

Results

Sedimentology

Sägistalsee sediments consist of brownish light gray, yellowish-brown, and dark brown to black, partly sandy and partly clayey, laminated silts (Fig. 2). Sediment colour is lighter at the bottom (Fig. 2a) and darker at the top (Fig. 2c) of the core with a gradual transition between 6 and 10 m sediment depth. Bulk dry densities of the sediments vary between 2.60 and 2.70 g cm^{-2} with an average of 2.65 g cm^{-2}. The 13.5 m sediment record represents the last 9050 years (Lotter and Birks, 2003). It is marked by continuous, clastic sedimentation and is laminated throughout the entire core. Laminae thickness ranges from 1–10 mm. Laminations are not regular throughout the core. Short intervals (up to 10 laminae) of rhythmites (R in Fig. 2) alternate with graded beds of up to 1 cm thickness (G in Fig. 2) and with sections of micro-lamination (M in Fig. 2) of less than 1 mm. Layer couplets within the rhythmites are about 1 mm thick. They exhibit a brownish, gray base and a thin black top. Contacts between individual lami-

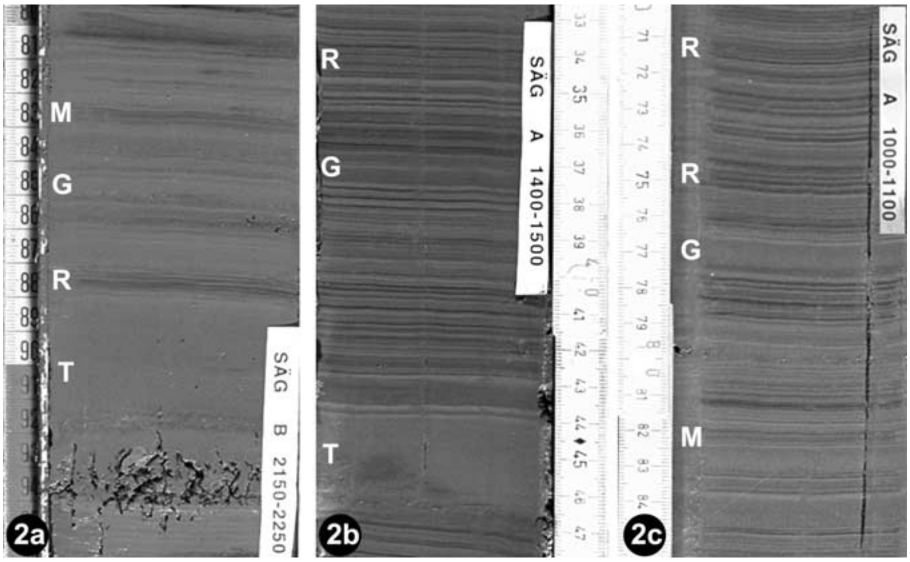

Fig. 2. Close-up photographs of laminated Sägistalsee sediments from three different levels of the core. (a) sediment at 9020 cal. BP. (b) sediment at 3600 cal. BP. (c) sediment at 800 cal. BP. R = rhythmites; G = graded beds of up to 1 cm thickness; M = microlamination of less than 1 mm thickness; T = turbidites with thicknesses between 1 and 5 cm. Scales in centimeters.

nae are sharp. About 25 turbidites (T in Fig. 2), between 1 and 5 cm thick, are intercalated in the entire sediment section. Turbidites show a thick, light brown to gray sandy basal layer, grading upwards and a light gray clay cap. Successions of laminated silts, intercalated by a few, massive turbidites and frequent occurrence of graded beds, several mm thick, are representative of seasonally stratified lakes, which are dominated by discontinuous detrital influx from rivers (Sturm and Matter, 1978; Sturm, 1979).

Geochemistry

Two opposing general trends are observed in the inorganic carbon concentrations (C_{inorg}) and organic carbon concentrations (C_{org}) (Figs. 3a and 3b). C_{org} concentrations increase up core from 0.7% at the bottom to 1.8% at the top, whereas C_{inorg} concentrations decrease from 5.6 to 3.5%. Both trends are strongly developed in the lower part of the core, but are weak in the upper part, above 4500 cal. BP. The amplitudes of fluctuations are small in the lower part but significantly higher in the upper part. The most prominent feature is a C_{inorg} minimum centred at 3700 cal. BP, followed by a C_{inorg} maximum centred at 3200 cal. BP. The latter coincides with a minimum in C_{org} concentrations, whereas during the C_{inorg} minimum C_{org} values are only slightly elevated. This oscillation in the C_{inorg} stratigraphy is part of a saw-tooth pattern that is a characteristic feature of the upper part of the core. Gradual decreases of C_{inorg} concentrations are interrupted by relatively abrupt increases towards the top of the core. In total this occurs four times in the past 4500 years (areas shaded in gray in Figs. 3, 5 and 6). C_{inorg} minima are observed at 3700, 2000, 650, and 150 cal. BP and maxima at 3200, 1450, 550 cal. BP and in the surface sediments (AD 1996). In general, the C_{org} stratigraphy is a mirror image of this pattern except for the last 350 years where both parameters show increasing values towards the sediment surface.

BSi concentrations in Sägistalsee sediments (Fig. 3c) are very low, showing a maximum of 0.7% between 2000 and 3000 cal. BP. No diatom frustules were found throughout the entire core, with the exception of the topmost sample.

Mineralogy

Calcite and quartz dominate the sediments of Sägistalsee. XRD peak intensities, which are semi-quantitative measures of mineral concentrations (Fanning et al., 1989), show that these two minerals constitute > 80% of the sediment mineralogy. The rest is composed of minor amounts of chlorite, mica, and mixed layer minerals. The presence of a peak at 4.46Å detected in a number of samples is interpreted as an indication for the occurrence of illite-montmorillonite.

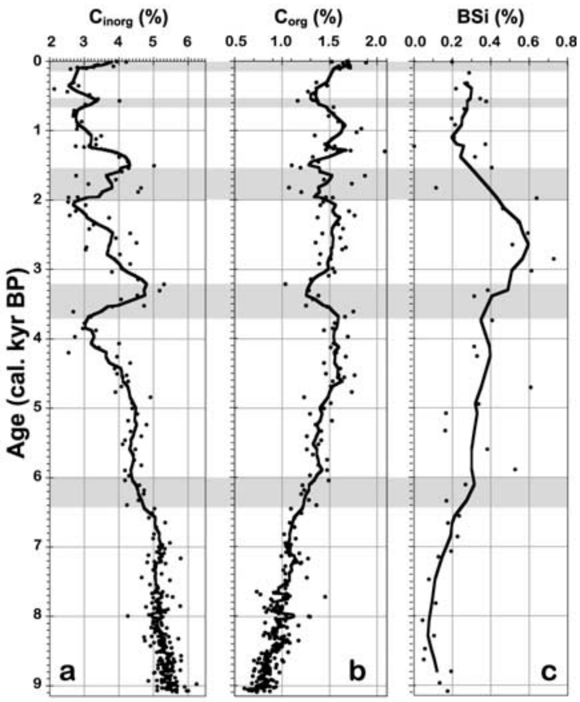

Fig. 3. Concentrations of (a) organic carbon (C_{org}), (b) inorganic carbon (C_{inorg}), and (c) biogenic silica (BSi). Black dots depict raw data; heavy black lines represent running means (n = 5).

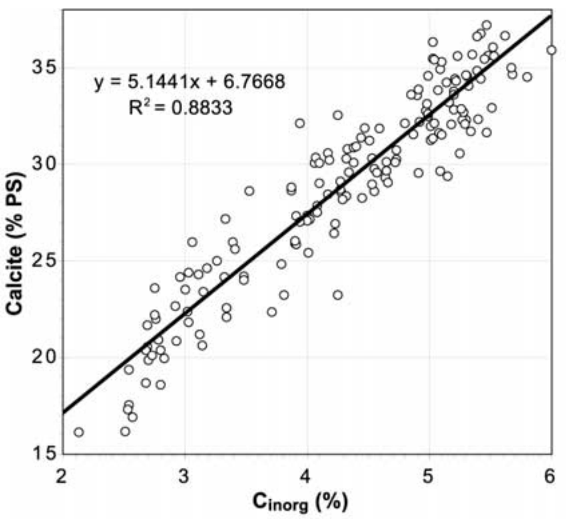

Fig. 4. The scatter plot of C_{inorg} measured with a coulometer vs. the intensity of the calcite 100% peak at 3.03Å determined by XRD shows a significant positive correlation ($r^2 = 0.88$) between these two parameters.

The calcite 100%-peak (peak intensity in cps at 29.406°2Θ/sum of all peak intensities) is positively correlated ($r^2 = 0.88$) with total inorganic carbon (C_{inorg}) concentrations (Fig. 4). This suggests that the entire inorganic carbon in the sediment is represented by calcite. There is no indication for the presence of other carbonate minerals (e.g., dolomite, siderite).

The Cc/Qz ratio (Fig. 5a) ranges between 0.4 and 2.2, indicating a shift from a calcite-dominated to a more quartz-dominated system. In the lower part of the core the Cc/Qz ratio averages 1.68 with a maximum of 2.2 and decreases to values as low as 0.4 near the top.

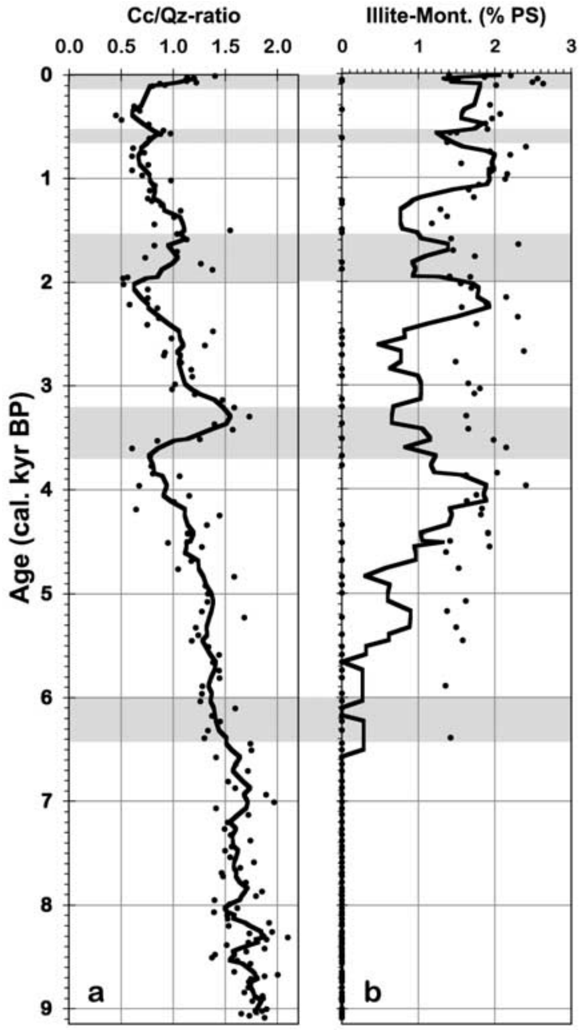

Fig. 5. Mineralogy determined by XRD. Shown is (a) the calcite/quartz-ratio (Cc/Qz) and (b) the relative intensity of the illite-montmorillonite peak at 4.46Å (see text for explanations). Black dots depict raw data; heavy black lines represent running means (n = 5).

The most prominent feature in the Cc/Qz ratio is a fluctuation where a maximum is reached at 3200 cal. BP that is preceded by a minimum at 3700 cal. BP.

Iillite-montmorillonite (Fig. 5b) was not observed prior to 6400 cal. BP. Afterwards its relative abundance increases regularly until 4000 cal. BP and then fluctuates towards the top of the core.

Grain size

Compared to other high Alpine lakes that were studied in the AQUAREAL project, the Sägistalsee sediments are relatively fine grained. The grain-size median (Fig. 6a) ranges from 4.3 to 26 µm with an average of 7.8 µm. For comparison, sediments of Hinterburgsee, a lake in the vicinity of Sägistalsee at 1630 m a.s.l., show a median of 20.1 ± 18 µm. On average the sediments consist of 81% silt, 15% clay, and 4% sand. Grain-size fractions (Figs. 6b–6d) between 6800 and 6300 cal. BP show a shift towards finer grained sediments, which is mainly caused by a drop in the sand content from 5.8 ± 3.0 to 2.3 ± 2.0%. A more detailed look at specific grain-size fractions reveals that a strong increase of the < 10 µm fraction (Fig. 6e) and a decrease of the 20–63 µm fraction (Fig. 6f) does also occur at this level.

The most prominent feature in the upper part of the core is a zone of very low median values (Fig. 6a) between 3950 and 3500 cal. BP. In this interval sand concentrations are below 1% (Fig. 6d) and low values of the 20–63 µm fraction (Fig. 6f) and correspondingly high percentages of the < 1 and 1–2 µm fraction (not shown) are observed.

Correlation

Within the lower part of the core, between 9050 and 6400 cal. BP, the content of C_{inorg} is positively correlated with the percentage of the 20–63 µm (coarse silt) fraction (Fig. 7), whereas between 0 and 6400 cal. BP the correlation between these two parameters is weak.

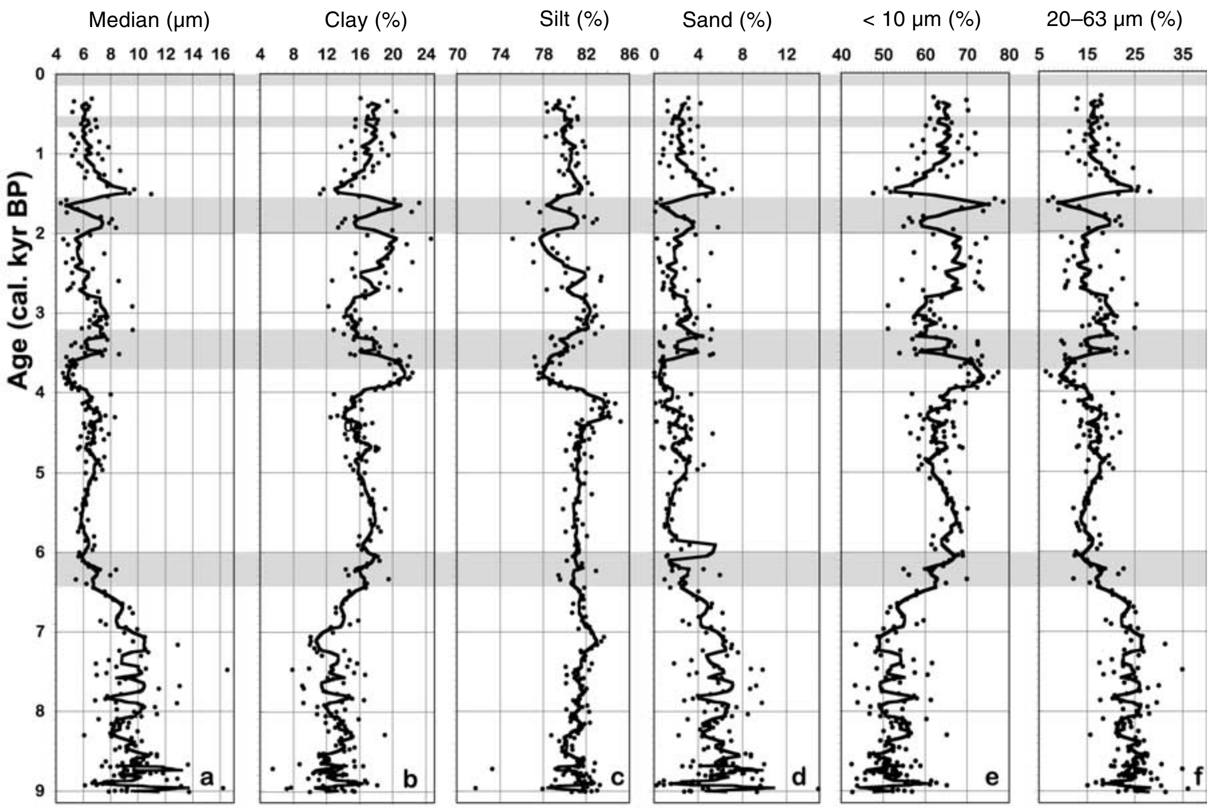

Fig. 6. Sediment grain size distribution. Shown are (a) the median grain size (d50) and the percentages of (b) clay (< 2 µm), (c) silt (2–63 µm), (d) sand (> 63 µm), (e) the < 10 µm fraction and (f) the 20–63 µm fraction. Black dots depict raw data; heavy black lines represent running means (n = 5).

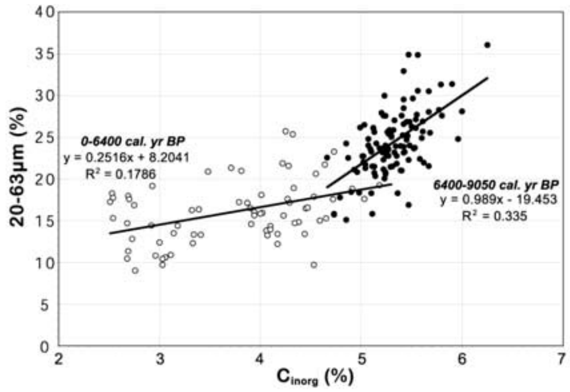

Fig. 7. Relationship between C_{inorg} concentration and the percentage of the grain size fraction 20–63 µm. Black dots represent the lower part of the core (6400–9050 cal. BP) with a significant correlation ($r^2 = 0.34$). Open circles represent the upper part (AD 1996 – 6400 cal. BP) with a weak correlation ($r^2 = 0.18$).

Discussion

Two main sedimentary rock types are distinguished in the Sägistalsee catchment (Fig. 1). The occurrence of almost pure limestone on the steep slopes is in contrast to the siliceous schist and marl forming the flatter parts of the catchment, where the two tributaries enter the lake. Dispersed hill-slope erosion mainly affects the steeper parts of the catchment and produces coarser particles with a high carbonate content, whereas stream channel erosion occurs in the flatter parts of the catchment and is responsible for the transport of finer particles with a lower carbonate content. Selectivity of chemical weathering is another important factor, which influences the mineralogy of particles (Garrels and MacKenzie, 1967). Carbonates may readily be dissolved during chemical weathering so that even the upper soil horizons, developed on carbonaceous rocks, are free of carbonate (St. Arnaud and Sudom, 1981). Together these mechanisms can affect the amount of carbonate particles that reach the lake, which is reflected in the Cc/Qz ratio of the sediments.

Based on these considerations and the observed sedimentological features, we interpret changes in the C_{inorg} concentration, grain size, and mineralogy (especially the Cc/Qz-ratio) of the Sägistalsee sediments mainly as a signal of catchment erosion. Lake internal changes have influenced the sediment properties only to a limited extent. Periods of marked changes in catchment erosion are shaded in gray in Figs. 3, 5 and 6. From the bottom to the top these are interpreted as follows.

The gradual decrease in C_{inorg} concentration (Fig. 3) and Cc/Qz ratio (Fig. 5) between 9050 and 3700 cal. BP is accompanied by a stepwise fining of grain size (Fig. 6). This is considered to be the result of both (1) a shift from mainly physical to more chemical weathering (see Koinig et al., 2003) and (2) a shift in the source of particles that reached the lake.

A shift of grain-size parameters (Fig. 6) and mineralogy (Fig. 5b) in this interval occurs at 6400 cal. BP and may have been caused by a change in catchment vegetation. Wick et al. (2003) describe a change from open woodlands with poorly developed soils to a well developed *Pinus cembra – Picea abies – Abies alba* forest with stabilized soils that established between 6400 and 6000 cal. BP. Prior to 6400 cal. BP particles may have reached the lake mainly by diffuse erosion from the steep carbonaceous slopes, as indicated by the coarse grain size (Fig. 6) and high Cc/Qz-ratio (Fig. 5a).

With increasing vegetation cover and stabilization of slopes after 6400 cal. BP, slope erosion became less important. Lowering of the Cc/Qz-ratio (Fig. 5a) and decreasing amounts of sand (Fig. 6d) and coarse silt (Fig. 6f) suggest that the source of particles was shifted from slope run-off towards the two tributaries. Here the finer grained dark, carbonaceous schist and marl with lower carbonate but a higher quartz, phyllosilicate, and clay mineral content were eroded. This interpretation is supported by the positive correlation of C_{inorg} concentrations with the 20–63 µm fraction prior to 6400 cal. BP, as opposed to a weak correlation after 6400 cal. BP (Fig. 7). The first appearance of illite-montmorillonite in the sediments indicates also an intensification of soil formation. Moreover, carbonate dissolution is particularly rapid in the acid soils that develop under coniferous vegetation, as was the case after *Picea abies* immigrated into the Sägistalsee catchment. Thus the input of detrital carbonate particles to the lake was progressively reduced with increasing catchment stabilization after 6400 cal. BP. Sediment mineralogy gradually shifted from a calcite-dominated to a more quartz-dominated system until 3700 cal. BP (Fig. 5a).

The first human activity in the catchment of Sägistalsee with indications of pasturing and cutting of trees is documented during the Neolithic period starting at 4300 cal. BP (Wick et al., 2003). Subsequently, the character of the sediments changes gradually as a result of the increasing erosion of the relatively fine grained and decalcified topsoil in the catchment. This is indicated by a decreasing Cc/Qz ratio, and decreasing values of C_{inorg}, sand, and coarse silt and increasing clay percentages (after 4100 cal. BP). Moreover, illite-montmorillonite (Fig. 5b) which would be enriched in the topsoils of the catchment, occurs more frequently around 4000 cal. yr BP. Slightly higher C_{org} values occurring at the same time, may also be the result of human-induced changes in the catchment that might have increased the nutrient input to the lake. This trend continues until 3700 cal. BP, when the Cc/Qz ratio (Fig. 5a) decreases below 1.0, and sand as well as coarse silt concentrations drop to very low levels. The absence of chironomids (Heiri and Lotter, 2003) and a low Mn/Fe ratio (Koinig et al., 2003) suggest that the lake bottom-water might have been anoxic for extended periods of time during the year. It was demonstrated by Ohlendorf et al. (2000) that anoxia, which promotes the dissolution of carbonate particles, develops during prolonged periods of ice cover in nearby high altitude Hagelseewli. Hence, it is possible that the decreasing sedimentary C_{inorg} concentrations in Sägistalsee are, to some extent, the result of calcite dissolution at the sediment/water interface and thus reflect anoxic conditions due to exceptionally long periods of ice cover. In addition, the lowering of the Cc/Qz-ratio and the decreasing median grain size suggest that erosional input was restricted to the tributaries between 4300 and 3700 cal. BP. We assume that during this time interval human impact was at a low level and only the topsoil was affected by erosion.

This trend changed abruptly at 3700 cal. BP when high amounts of charcoal in the sediments mark a major deforestation of the catchment in the Bronze Age (Wick et al., 2003). Soon afterwards a sudden increase of the Cc/Qz ratio, the coarsening of grain sizes, and a less frequent occurrence of illite-montmorillonite is observed in the sediments. This indicates the erosion of unweathered soils and/or bedrock, most likely with a significant contribution from the steeper, more carbonaceous parts of the catchment. The sediment Cc/Qz ratio increases by a factor of 2 in less than 100 years, reaching peak values at 3200 cal. BP. Chironomid analyses and geochemistry results indicate better-oxygenated bottom-water around the same time (Heiri and Lotter, 2003; Koinig et al., 2003). This might be the result of a more frequent occurrence of density underflows, which happen when the concentration of suspended sediment in a tributary is so large that its density is much higher than that of the lake water. The resulting underflows then lead to oxygen replenishment of the bottom water. After 3200 cal. BP the gradually decreasing Cc/Qz ratio (Fig. 5a) and decreasing silt percentages (Fig. 6c) indicate a slow recovery (soil formation) of the catchment until 2000 cal. BP. Again the increased abundance of illite-montmorillonite between 2400 and 2000 cal. BP indicates the beginning erosion of topsoils (Fig. 4d). During this interval the highest BSi concentrations are observed, which indicates more productivity and thus higher nutrient levels in the lake. This is probably the result of the intensification of pasturing (Wick et al., 2003) and the associated input of cow manure (Heiri and Lotter, 2003) in the vicinity of Sägistalsee. As described above, geochemical and biological proxies (Heiri and Lotter, 2003; Koinig et al., 2003) indicate oxygen deficiencies in the bottom water. After 2000 cal. BP, an increasing Cc/Qz-ratio, grain-size coarsening, and a lower illite-montmorillonite abundance suggest a second erosion period that involved the erosion of unweathered soil and bedrock. Erosion peaks at 1450 cal. BP, and it probably reflects forest clearances during the early Middle Ages (Wick et al., 2003). BSi levels drop during this event and remain low until today, probably due to a strong dilution by clastic input. The third and most recent stabilization/erosion cycle has a Cc/Qz-ratio minimum in the 19th century and a maximum in the surface sediments. The stabilization trend shows a short interruption with an increasing Cc/Qz ratio between 650 and 550 cal. BP, marking an intensification of pasturing during medieval times (Wick et al., 2003), followed by the abandonment of high Alpine meadows during the ‘Little Ice Age’ cooling. The increasing Cc/Qz ratio during the past 150 years may then be viewed as response to increasing human activity (e.g., agriculture, tourism) in the catchment again.

Conclusions

The sedimentological analysis of Sägistalsee sediments combined with palynological, geochemical, and palaeobiological information (Heiri and Lotter, 2003; Koinig et al., 2003; Wick et al., 2003) allows the following general conclusions:

Holocene environmental changes are recorded in the sediments of Sägistalsee indirectly through changes in catchment vegetation, which influence the weathering and erosional regimes. The Cc/Qz-ratio has been found to be a good indicator of changes in the prevailing erosion mode and permits two different periods in the lake’s sedimentary record to be distinguished.

Prior to 4300 cal. BP, the sediment chemistry and mineralogy show only slow and gradual changes that are associated with the natural expansion of vegetation. In contrast, after 4300 cal. BP human impact in the catchment leads to large and abrupt fluctuations. Changes in the Cc/Qz-ratio follow a saw-tooth pattern, i.e., short event-like disturbances are followed by long periods of gradual recovery. According to Dearing (1991) this is indicative of human impact on natural systems. Lowering of the Cc/Qz-ratio, an increase of finer grain sizes, and the more frequent occurrence of illite-montmorillonite pre-date heavy erosion events by several 100 years and are indicative of the beginning of topsoil erosion.

The absence of large and rapid sedimentological changes in the pre-human impact period, demonstrates that natural environmental variability in the Sägistalsee region, which is mainly driven by climate change, is of a lower magnitude than changes induced by human activities in the catchment.

Acknowledgements

We gratefully acknowledge assistance in the field and in the laboratory of I. Holderegger, P. Inauen, G. Lemcke, A.F. Lotter, A. Zürcher, A. Zwyssig. We thank A.M. Hirt, O. Heiri, K.A. Koinig, L. Lanci, D. Livingstone, W. Van der Kaap, J. van Leeuwen and L. Wick for providing access to their data and for insightful discussions. We are grateful to the two reviewers D. Engstrom and W. Dean for their critical comments on the first draft, which significantly improved the paper.

This research was made possible by the Swiss National Science foundation within the framework of Priority Program Environment grant 5001-44600 and by the European Union Environment and Climate project 'CHILL 10,000' (Climate history as recorded by ecologically sensitive arctic and alpine lakes during the last 10,000 years: a multi-proxy approach; contract No. ENV4-CT97-0642). This is CHILL contribution 39.

References

Beniston M., Diaz H.F. and Bradley R.S. 1997. Climatic change at high elevation sites: an overview. Clim. Change 36: 233–251.

Conley D.J. 1988. Biogenic silica as an estimate of siliceous microfossil abundance in Great Lakes sediments. Biochem. 6: 161–179.

Dearing J.A. 1991. Lake sediment records of erosional processes. Hydrobiologia 214: 99–106.

DeMaster D.J. 1981. The supply and accumulation of silica in the marine environment. Geoch. Cosmoch. Acta. 45: 1715–1732.

Fanning D.S., Keramidas V.Z. and El-Desoky M. 1989. Micas. In: Dixon J.B. and Weed S.B. (eds), Minerals in Soil Environments. Soil Science Society of America, Madison, Wisconsin, pp. 551–634.

Garrels R.M. and MacKenzie F.T. 1967. Origin of the chemical composition of some springs and lakes. In: Gould R.F. (ed.), Equilibrium Concepts in Natural Water Systems. American Chemical Society, Washington D.C.. Adv. Chem. Ser. 67, pp. 222–242.

Gobet E., Hochuli, P.A. and Ariztegui D. 2001. Human Impact on the Vegetation of the Upper Engadine (Central Swiss Alps). EUG XI, J. Conf. Abs. 6: 128.

Günzler-Seiffert H. and Wyss R. 1938. Erläuterungen zur geologische Karte von Grindelwald, Blatt 396, Geologischer Atlas der Schweiz 1:25000 13, Bern.

Guthruf J., Guthruf-Seiler K. and Zeh M. 1999. Kleinseen im Kanton Bern. Gewässer und Bodenschutzlabor, Amt für Gewässerschutz und Abfallwirtschaft des Kantons Bern, 229 pp.

Heiri O. and Lotter A.F. 2003. 9000 years of chironomid assemblage dynamics in an Alpine lake: long-term trends, sensitivity to disturbance, and resilience of the fauna. J. Paleolim. 30: 273–289.

Hirt A.M., Lanci L. and Koinig K. 2003. Mineral magnetic record of Holocene environmental changes in Sägistalsee, Switzerland. J. Paleolim. 30: 321–331.

Hofmann W. 2003. The long-term succession of high-altitude cladoceran assemblages: a 9000 year record from Sägistalsee (Swiss Alps). J. Paleolim. 30: 291–296.

Koinig K., Shotyk W., Lotter A.F., Ohlendorf C. and Sturm M. 2003. 9000 years of geochemical evolution of lithogenic major and trace elements in the sediments of an alpine lake – the role of climate, vegetation, and land use history. J. Paleolim. 30: 307–320.

Leemann A. and Niessen F. 1994. Holocene glacial activity and climatic variations in the Swiss Alps: reconstructing a continuous record from proglacial lake sediments. The Holocene 4: 259–268.

Leonard E.M. and Reasoner M.A. 1999. A continuous Holocene Glacial Record Inferred from Proglacial Lake Sediments in Banff National Park, Alberta, Canada. Quat. Res. 51: 1–13.

Leonard E.M. 1986. Varve studies in Hector Lake, Alberta, Canada, and the relationship between glacial activity and sedimentation. Quat. Res. 25: 199–214.

Lotter A., Ammann B., Birks H.J.B., Heiri O., Hirt A., Lanci L., Lemcke G., Sturm M., van Leeuwen J.F.N., Walker I.R. and Wick L. 1997. AQUAREAL: A multi-proxy study of Holocene sediment archives in Alpine lakes. Würzburger Geogr. Manuskripte 41: 127–128.

Lotter A.F. and Birks H.J.B. 2003. Holocene sediments of Sägistalsee, a small lake at present-day tree-line in the Swiss Alps. J. Paleolim. 30: 253–260.

Ohlendorf C., Niessen F. and Weissert H. 1997. Glacial Varve Thickness and 127 Years of Instrumental Climate Data: A Comparison. Clim. Change 36: 391–411.

Ohlendorf C., Bigler C., Goudsmit G.H., Lemcke G., Livingstone D.M., Lotter A.F., Müller B. and Sturm M. 2000. Causes and effects of long ice cover on a remote high Alpine lake. J. Limnol. 59: 65–80.

Seeber H. 1911. Geologische Kartenskizze desGebietes östlich vom Lauterbrunnental 1:50000. Geogr. artist. Anstalt Kümmerly & Frey, Bern.

St. Arnaud R.J. and Sudom M.D. 1981. Mineral Distribution and Weathering in Chernozemic and Luvisolic Soil from Central Saskatchewan. Can. J. Soil Sci. 61: 79–89.

Sturm M. and Matter A. 1978. Turbidites and varves in Lake Brienz (Switzerland): deposition of clastic detritus by density currents. Spec. Pub. Int. Ass. Sed. 2: 147–168.

Sturm M. 1979. Origin and composition of clastic varves. In: Schlüchter Ch. (ed.), Moraines and Varves. A.A. Balkema, Rotterdam, pp. 281–285.

Tinner W. and Ammann B. 1996. Treeline fluctuations recorded for 12,500 years by soil profiles, and plant macrofossils in the central Swiss Alps. Arct. Alp. Res. 28: 131–147.

Wick L., van der Knaap W.O., Leeuwen J.F.N. and Lotter A.F. 2003. Holocene vegetation development in the catchment of Sägistalsee (1935 m a.s.l.), a small lake in the Swiss Alps. J. Paleolim. 30: 261–272.

Wick L. and Tinner W. 1997. Vegetation changes and timberline fluctuations in the Central Alps as indicators of Holocene climatic Oscillations. Arct. Alp. Res. 29: 445–458.

Wyss R. 1990. Die frühe Besiedlung der Alpen aus archäologischer Sicht. Mit 17 Abbildungen. Siedlungsforschung Archäologie-Geschichte-Geographie 8: 69–86.

Zar J. 1984. Biostatistical Analysis. Prentice-Hall, New Jersey, 718 pp.